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Research on tire quality evaluation method for lateral force coefficient test

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Abstract. This paper conducts research on the quality evaluation method of tires used in lateral force coefficient testing. By applying the analytic hierarchy process (AHP), a comprehensive tire quality evaluation system was established, taking into account the chemical properties, physical and mechanical properties, and measurement uniformity of the tires. This system breaks the limitation of traditional single-factor evaluation and accurately reflects the quality of the tested tires. The AHP method shows good adaptability in the evaluation, determining the reasonable weight of each evaluation factor for the tested tires produced by different manufacturers in the lateral force coefficient testing scenario, such as the factors related to lateral force in physical and mechanical properties, the chemical composition of anti-wear chemical substances and measurement uniformity, which have a key impact on the test results. In addition, it achieves an organic combination of quantitative and qualitative factors by rationally quantifying qualitative factors and combining them with quantitative data, making the evaluation results more scientific and convincing, and effectively avoiding evaluation biases. It provides a reliable basis for the selection and quality control of tested tires.

1. Introduction

When the single-wheel transverse force coefficient tester works, the test wheel and the vehicle driving direction are 20-deflection Angles, the road will form an axial parallel force on the test wheel, and the transverse force coefficient (SFC) can be obtained by calculating the ratio of the parallel force and the vertical force. It is suggested that the transverse force coefficient SFC should be used as the test index of the anti-skid performance of the road surface. JT/T 752-2009 “Test tire of sideway-force coefficient routine investigation machine” [1]has been released and implemented for 14 years, and China has the ability to produce single-wheel transverse force coefficient tester to test tires. At present, the single-wheel lateral force coefficient tester used in our country mainly comes from 5 manufacturers, but the quality of the test tires produced by these five manufacturers is uneven. China’s road engineering inspection based on the standard requirements of cement concrete pavement general section acceptance can not be less than 50, but under the same conditions, different manufacturers test tire measured transverse force coefficient difference maximum to 10. In the event of using poor quality test tires, it is bound to make the measured transverse force system value and the actual value of a big difference, failing to truthfully reflect the real anti-skid performance of the road surface, not only for driving safety risks, but also lead to road maintenance and maintenance to make wrong decisions[2,3]. In this paper, the transverse force coefficient test tire used in our country is analyzed from three aspects: chemical composition, physical and mechanical properties, and measurement uniformity. The analytic hierarchy process is used to evaluate the quality of the test tire, so as to achieve the purpose of standardizing tire production and improving the accuracy of the evaluation of road anti-skid performance.

2. Analysis of test tire quality evaluation elements

Test tire quality evaluation is a comprehensive process, and its input elements cover several key aspects.

First of all, chemical performance is an important part, and it is related to the material composition and characteristics of the tire, such as the formula of rubber, the use of various additives, etc. These chemical factors directly affect the durability of the tire, its anti-aging ability, and its adaptability to different environmental conditions[4,5].

Secondly, the physical and mechanical properties occupy an important position in the evaluation. This includes the tire's hardness, elasticity, tensile strength, wear resistance, and other indicators. The hardness determines how supportive the tire will be when it comes into contact with the road; Elasticity affects its cushioning and damping effect; The tensile strength is related to the deformation resistance of the tire when bearing the load; The wear resistance is directly related to the service life of the tire[6~9].

Finally, the final output value of test tire use is its interaction with the road surface, producing a transverse force coefficient. The uniformity of the measured value is an element that cannot be ignored. These factors are related to each other and together constitute an important basis for tire quality evaluation.

2.1. Analysis of test tire quality evaluation elements

The test results of the chemical composition of the tires from 5 manufacturers are shown in Table 1.

Table 1. Chemical composition of tires from different manufacturers.

Name	Manufacturer S	Manufacturer J	Manufacturer Z	Manufacturer L	Manufacturer H
Natural glue	56.28	56.1	46.38	48.6	58.4
Carbon black	30.73	29.28	34.77	32.7	28.7
Combined sulfur	1.64	1.24	1.25	1.56	1.03
Zinc oxide	2.97	2.18	2.24	2.15	4.6
Silica	0	0.055	0.94	2.65	0

2.2. Analysis of physical and mechanical properties

According to JT/T 752-2009, the main physical and mechanical properties of tires include tensile strength, hardness, wear, tear strength, elasticity, and hot air aging 100°C×24h tensile strength reduction rate. The physical and mechanical properties test results of different manufacturers' tires are shown in Table 2.

Table 2. Physical and mechanical properties of tires from different manufacturers.

Name	Manufacturer S	Manufacturer J	Manufacturer Z	Manufacturer L	Manufacturer H
Tensile Strength (MPa)	20.9	20.4	19.8	16	16.5
Wear (cm^3)	0.278	0.144	0.114	0.415	0.058
Elasticity (%)	52	39	25	31	41
Hot air aging 100°C×24h tensile strength reduction rate (%)	-49	-14	-8	-20	-24.8

2.3. Uniformity of measurement

The same single-wheel lateral force coefficient tester and the same tester are used to conduct uniform testing on different test tires in the same period of time. Each manufacturer chooses 5 test tires and tests each tire 7 times. The measured data are calculated according to the manufacturer's average value and standard deviation. The measured data are summarized and processed, and the test results are shown in Table 3.

Table 3. Test data of tire uniformity.

Manufacturer name	Manufacturer S	Manufacturer J	Manufacturer Z	Manufacturer L	Manufacturer H
The average value of the transverse force coefficient	52.12	51.22	63.37	54.18	52.21
The standard deviation of the transverse force coefficient	2.88	0.80	3.23	0.69	3.16

3. Calculation of weight of quality evaluation elements

The analytic hierarchy process (AHP) is an effective method to decompose complex problems into multiple levels and multiple factors, as well as carry out comprehensive evaluation. Tire quality evaluation involves many aspects, such as chemical properties, physical and mechanical properties, and uniformity of measured values. The analytic hierarchy process (AHP) can integrate these factors of different properties into one evaluation system. The analytic hierarchy process (AHP) can systematically consider the interrelationship between these factors and avoid the situation of only focusing on a single factor while ignoring other important factors. With tire quality as the overall goal, chemical properties, physical and mechanical properties, and measurement uniformity as the criterion layer, each criterion layer can be subdivided. For example, the physical and mechanical properties can be subdivided into multiple sub-factors, which align with the analytic hierarchy process's characteristics and are convenient for hierarchical evaluation. It can first analyze the performance of sub-factors, then synthesize the scores of each criterion layer, and finally get a comprehensive evaluation of tire quality[10,11].

3.1. Construction of evaluation index system

The quality index system of the tire is analyzed in three parts: chemical composition, physical and mechanical properties, and measurement uniformity. The index system created is shown in Table 4.

Table 4. Tire quality evaluation index system.

	Grade 1 index	Secondary indicators
Tire quality evaluation index K	Chemical Composition A	Natural glue A1
		Carbon Black A2
		Bound Sulfur A3
		Zinc oxide A4
		Silica A5
	Physical and mechanical Properties B	Tensile strength B1
		Hardness B2
		Wear B3
		Tear strength B4
		Elasticity B5
		Hot air aging 100℃×24h tensile strength reduction rate B6
	Uniformity of measurement C	Coefficient of variation of measured values C1

3.2. Determination of the dimension weight of first-level indicators

The pairwise matching comparison method is used to compare and score the elements of the same level according to the 1-9 ratio scale, and the judgment matrix is constructed. Determine the weight of chemical composition, physical and mechanical properties, and uniformity of measured values. By assigning values to the three aspects of the investigation results, the judgment matrix is obtained, as shown in Table 5 below[12].

Table 5. Judgment matrix.

	Chemical composition	Physical mechanical properties	Uniformity of measurement
Chemical composition	1	1/2	1/4
Physical mechanical properties	2	1	1/2
Uniformity of measurement	4	2	1

SPASSRO was used to perform hierarchical analysis on the matrix, and the results of AHP hierarchical analysis are shown in Table 6.

Table 6. Results of AHP hierarchy analysis.

First level index Name	Feature vector	Weight value (%)	Maximum feature root	CI value
Chemical composition	0.429	14.286	3	0
Physical mechanical properties	0.857	28.571		
Uniformity of measurement	1.714	57.143		

The AHP results show the relative importance of each evaluation index (chemical composition, physical and mechanical properties, uniformity of measured value) when the tire quality is comprehensively evaluated by AHP[13,14]. The eigenvector directly reflects the weight distribution in the evaluation system of each factor, while the weight value further quantifies the relative importance and provides a scientific basis for decision-making. Specifically, the weight of chemical composition is 14.286%, indicating that although it is a crucial factor to consider in the overall evaluation system, its degree of influence is relatively low. The weight of physical and mechanical properties reached 28.571%, indicating its medium importance in the evaluation system, which may be a concern because it directly affects the performance and durability of the product. The most significant is the uniformity of measurement. Its weight is as high as 57.143%, occupying the dominant position of the evaluation system, which reflects that the uniformity of measurement has a significant influence and decisive role in the evaluation results and is directly related to the quality control of products. In addition, the maximum feature root value is 3, which is consistent with the number of evaluation factors, indicating that the constructed hierarchical structure model is logically consistent without significant unreasonable or contradictory situations. According to the RI table, the corresponding RI value is 0.525, so CR=CI/RI=-0.0 < 0.1, indicating that the relative importance evaluation among various factors is entirely consistent, and there is no internal conflict or inconsistent evaluation, which further verifies the reliability and effectiveness of the analytic hierarchy model.

3.3. Determination of the dimension weight of the secondary index

(1) Determination of chemical component dimension index weight

The weight analysis results of chemical component dimension indicators are shown in Table 7.

Table 7. Weight and normalization results of the secondary index layer (chemical composition).

Categories	Natural Glue A1	Carbon Black A2	Bound Sulfur A3	Zinc oxide A4	Silica A5
Natural glue A1	1	1/3	0.5	0.5	1
Carbon Black A2	3	1	1.5	1.5	3
Bound Sulfur A3	2	2/3	1	1	2
Zinc oxide A4	2	2/3	1	1	2
Silica A5	1	1/3	1/2	1/2	1

SPASSRO was used to perform hierarchical analysis on the matrix, and the results of AHP hierarchical analysis of chemical components were obtained, as shown in Table 8.

Table 8. Results of AHP hierarchy analysis of chemical components.

Categories	Feature vectors	Weight values	Maximum feature root	CI value
Natural glue A1	0.556	11.111		
Carbon Black A2	1.667	33.333		
Bound Sulfur A3	1.111	22.222	5	0
Zinc oxide A4	1.111	22.222		
Silica A5	0.556	11.111		

In the application of the analytic hierarchy process, the data presented reveals the relative importance of the key factors affecting the tire. By constructing a hierarchy and calculating feature vectors and weights, the analysis assigns weights to factors such as natural rubber, carbon black sulfur, zinc oxide, etc. These weights reflect their relative importance in the overall evaluation of the system.

Firstly, the basic principle that the sum of all factors' weight values is 100 weight allocation is noted, which ensures the consistency and completeness of the evaluation. Specifically, carbon black dominates with a weight value of 33.333%, indicating that in the system of tire quality evaluation, carbon black is a key factor affecting performance, and its contribution is significantly higher than other components. Combined sulfur and zinc oxide followed with equal weight values (22.222% each), indicating that these two components also play an important role in tire production, but their impact is slightly less than that of carbon black. Natural gum and silica each have a weight of 11.111%, indicating that they have a relatively minor, but still essential, impact on tire performance.

The maximum feature root =5 indicates that the dimension of the constructed judgment matrix is 5, revealing that five main factors are considered. The calculation results of the analytic hierarchy process show that the maximum feature root is 5.0, and the corresponding RI value is 1.11 according to the RI table, so CR=CI/RI=0.0<0.1, passing the one-time test.

(2) Determine the weight of the physical and mechanical performance dimension index

The weight analysis results of physical mechanical performance dimension indicators are shown in Table 9.

Table 9. Weight and normalization results of the secondary index layer (chemical composition).

Categories	Tensile Strength B1	Hardness B2	Wear B3	Tear strength B4	Elasticity B5	Hot air aging 100°C×24h tensile strength reduction rate B6
Tensile strength B1	1	1/3	1/5	1/2	1/4	2
Hardness B2	3	1	3/5	3/2	3/4	6
Wear B3	5	5/3	1	5/2	5/4	10
Tear strength B4	2	2/3	2/5	1	1/2	4
Elasticity B5	4	4/3	4/5	2	1	8
Hot air aging 100°C×24h tensile strength reduction rate B6	1/2	1/6	1/10	1/4	1/8	1

SPASSRO was used to perform hierarchical analysis on the matrix, and the results of AHP hierarchical analysis of chemical components were obtained, as shown in Table 10.

According to the results of the analytic hierarchy process (AHP), the weight values of the physical and mechanical properties indicators show significant differences, reflecting the importance of different indicators in the comprehensive evaluation. There is a nonlinear conversion between the feature vector and the weight value, indicating that the feature vector is not directly equal to the weight percentage, but the weight value is obtained through normalization. The weight value directly reflects the relative importance of each evaluation index in the decision-making process.

Table 10. Results of AHP hierarchy analysis of physical and mechanical properties.

Category	**Feature vectors**	**Weight value (%)**	**Maximum feature root**	**CI value**
Tensile strength B1	0.387	6.452	6	0
Hardness B2	1.161	19.355		
Wear B3	1.935	32.258		
Tear strength B4	0.774	12.903		
Elasticity B5	1.548	25.806		
Hot air aging 100℃×24h tensile strength reduction rate B6	0.194	3.226		

The weight value of wear is 32.258%, which is the highest weight indicator, indicating that wear resistance is regarded as the most critical factor and has the greatest impact on the overall evaluation. This is in line with most material applications, and wear resistance is directly related to the service life and economic benefits of the material.

The weight value of elasticity is 25.806%, followed by its ability to show the ability of the material when it is subjected to external force, and it has a wide range of application values in the field of tires.

Hardness (weight value 19.355%) and tear strength (weight value 12.9%) ranked third and fourth, respectively, indicating that the rigidity and tear resistance of the material also play an important role in the evaluation of tire quality. Hardness affects the wear resistance of the material, while tear strength is directly related to the behavior of the material when subjected to tearing force.

The results are as follows: the tensile strength (weight value 6.452%) and hot air aging 100℃ 4h tensile strength reduction rate (weight value 3.226%). Although the weight is relatively low, it still can not be ignored factors. Tensile strength measures the bearing capacity of a tire when it is subjected to tensile forces*, w*hile the change in tensile strength after aging reflects the durability and stability of the tire.

The maximum feature root =6 indicates that the dimension of the constructed judgment matrix is 6, suggesting that six major factors are considered. The calculation results of the analytic hierarchy process show that the maximum feature root is 6.0, and the corresponding RI value is 1.25 according to the RI table, so CR=CI/RI=0.0<0.1, passing the one-time test.

3.4. Determination of weight results

As mentioned above, the weights of the three first-level indicators and their sub-indicators are calculated respectively, and the final weight results are shown in Table 11.

Table 11. Weight results of tire quality evaluation index system.

Grade 1 index	Tier 1 indicator Weight (%)	Level 2 indicators	Secondary indicator weight (%)	Comprehensive weight of secondary indicator	Weight = weight x 100
Chemical Composition A	14.286	Natural glue A1	11.111	0.02	2
		Carbon Black A2	33.333	0.05	5
		Bound Sulfur A3	22.222	0.03	3
		Zinc oxide A4	22.222	0.03	3
		Silica A5	11.111	0.02	2
Physical and mechanical Properties B	28.571	Tensile strength B1	6.452	0.02	2
		Hardness B2	19.355	0.06	6
		Wear B3	32.258	0.09	9
		Tear strength B4	12.903	0.04	4
		Elasticity B5	25.806	0.07	7

		Hot air aging 100°C×24h tensile strength reduction rate B6	3.226	0.01	1
Uniformity of measurement C	57.143	Coefficient of variation of measured values C1	1	0.57	56

4. Test the overall score of tire quality

After calculating the sub-score of the chemical composition, physical and mechanical properties and test uniformity of each manufacturer, the comprehensive score of the tire quality of each manufacturer is calculated, as shown in Table 12.

Table 12. Comprehensive score of tire quality of each manufacturer.

	Manufacturer S	Manufacturer J	Manufacturer Z	Manufacturer L	Manufacturer H
Chemical composition score by item	13.61229	11.09447	8.94292	6.35404	10.34613
Score the physical and mechanical properties	20.44887	21.65279	18.92407	13.74437	19.03437
Score the uniformity of the measured value	52.90560	55.12534	53.14565	55.28682	52.61061
Overall scoring	86.97	87.87	81.01	75.39	81.99

Note: Comprehensive score of tire quality = sub-score of chemical composition + sub-score of physical and mechanical properties + sub-score of measured value uniformity

From the calculation results, each dimension can be analyzed separately as follows:

(1) Manufacturer S has the highest chemical composition score (13.61), indicating that it has the best performance in this dimension. Factory L has the lowest chemical composition score (6.35), indicating its weak performance in terms of chemical composition.

(2) Manufacturer J has the highest score in physical and mechanical properties (21.65), indicating that its materials are superior in physical and mechanical properties. Manufacturer L has the lowest score (13.74) and is relatively poor in this respect.

(3) Manufacturer L has the highest evenness score (55.29), indicating that its products perform very well in the uniformity of measured values. The score of manufacturer H was the lowest (52.61), but the difference between the five manufacturers in this dimension was small, and all were between 52-55 points, indicating that the performance of all manufacturers in this aspect was relatively close.

(4) Manufacturer J has the highest comprehensive score (87.87), indicating that its performance in all dimensions is more balanced, and it is the best manufacturer on the whole. Manufacturer L has the lowest comprehensive score (75.39), indicating that its comprehensive performance is relatively poor. The scores of other manufacturers (S, Z, H) ranged from 81-87, indicating moderate performance.

Manufacturer J has outstanding performance in physical and mechanical properties and comprehensive scores, and is the supplier with the best overall performance. The scores of chemical composition and physical and mechanical properties of manufacturer L are relatively low, which affects its comprehensive score, and it is a relatively weak manufacturer. Although factory S is excellent in the chemical composition score, it is slightly inferior in uniformity and physical and mechanical properties, resulting in a slightly lower comprehensive score than factory J.

5. Conclusion

This study focuses on the tire quality evaluation method for the lateral force coefficient test. Through in-depth analysis and application of the analytic hierarchy process, the following important conclusions are drawn:

(1) The established tire quality evaluation system is effective for tire testing with lateral force coefficient. The system fully considers the chemical, physical, and mechanical properties and

measurement uniformity of these three main aspects, breaking through the limitations of the traditional single-factor evaluation. In practical application, this comprehensive evaluation method can fully and accurately reflect the performance of tire quality under the transverse force coefficient test environment and provide a reliable basis for the screening and quality control of high-quality tires.

(2) Analytic hierarchy Process shows good adaptability in the evaluation of tire quality for lateral force coefficient test. It can clearly present the hierarchical structure of tire quality evaluation elements, from the overall quality objective of the tire, to the criterion layer of chemical properties, physical and mechanical properties, and measurement uniformity, and then to the subdivision factors under each criterion. This structure helps to systematically analyze the relationship and importance of different factors and provides a clear logical framework for the evaluation process.

(3) The research successfully determined the reasonable weight of each evaluation factor. In the transverse force coefficient test scenario, the weight of each factor is different for different uses of tires. Factors related to lateral force in physical and mechanical properties (such as elasticity in a specific direction, local hardness distribution, etc.) have a greater weight, because they directly affect the accuracy of the transverse force coefficient test results. The chemical properties of the anti-wear chemical composition also have an important weight because of the impact on the long-term performance of the tire. The uniformity of the measurement value is the key to ensuring the stability of the test. The weight distribution is in line with the actual functional requirements of the tire in the transverse force coefficient test.

(4) The advantage of combining quantitative and qualitative. Through the analytic hierarchy process, the organic combination of quantitative and qualitative factors is realized. In the evaluation process, some qualitative factors of chemical properties are combined with quantitative data of physical and mechanical properties and measurement uniformity through reasonable quantification (such as scoring based on industry experience and expert judgment), which makes the whole evaluation result more scientific and convincing. This combination can more accurately reflect the quality level of the tire under the complex transverse force coefficient test conditions and effectively avoid the deviation caused by a single data type evaluation.

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